A MECHANICALLY FLEXIBLE, BATTERY-POWERED, DIFFERENTIAL ELECTRODE UNIT FOR ELECTROPHYSIOLOGICAL RECORDINGS

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*Abstrac*t-**This paper describes a new type of micro-powered electrode configuration. The circuit consists of an instrumentation amplifier and a special AC coupling configuration that maintains a high CMRR with a gain of a 1000. All electronics, including two lithium batteries, are mounted on a flexible circuit board (FPC). The single FPC has a special shape that allows differential recording at various distances between the electrodes. The whole circuit is typically popped onto EMG electrodes so that it can be re-used many times.**
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I. INTRODUCTION

The objective of this project was to design and implement a single and compact unit containing all the electronics required for surface EMG and in particular skeletal muscle signal pre-amplification. A sufficiently high gain had to be used without causing saturation. By using a high gain right next to the recording electrodes, it is likely that a much higher SNR would be achieved in most cases. The unit had to be powered by batteries while providing a relatively long operational life. Battery powered systems offer both very low noise on the power rails as well as providing isolation. Although the PSRR of the amplifier can reject noise from power rails, bringing power to the remote unit through relatively long wires would have noise at various frequencies that would likely not be fully attenuated by the PSRR and hence causing alias errors. The unit has also to be re-usable after each experiment. A high CMRR had to be achieved while providing slow baseline drift removal capability. The applications require a recording bandwidth up to 100 Hz at a minimum gain of 60 dB with an expected maximum signal amplitude up to +1 mV.

II. DESCRIPTION

A. Architecture

The general architecture of the active electrode configuration is shown in Fig. 1. The circuit, implemented on a single Kapton Flexible Printed Circuit (FPC), has two main sections of size 33.75 mm × 21.78 mm (1.3285 × 0.8575 inch) linked through a narrow bridge. One section contains all the electronics whereas the second section is used to hold two rechargeable lithium batteries. Both sections have an embedded female snapper as shown in the photograph that connects directly to a pair of conventional surface electrodes by inserting the female onto the male snappers. The configuration allows two differential electrodes to be placed on the skin apart to a chosen distance up to 101.6 mm. (4 inches). For shorter distances, the narrow bridge connecting the two sections simply bends upward.

B. Amplifier

One of the most critical issues was to select the best amplifier for this particular unit. The AD627 [1] has been selected for several reasons. The AD627 is a micro-power instrumentation amplifier, which makes it ideal for differential recordings while consuming low power. In dual supply mode, the power rails Vs can be as low as ±1.1 Volt, which is ideal for battery-powered applications. With a maximum quiescent current of 85 μA (60 μA typical), the unit can operate continuously for several hundred hours before requiring battery replacement.

C. Batteries

Although 1.5 V batteries such as Zinc-Air batteries or even 1.2 V nickel cadmium or nickel-metal hydrite (NiMH) batteries could have been used, 3.0 V batteries such as lithium cells have been chosen. With a gain of 60 dB and a maximum negative and positive output swing of -Vs + 25 mV and +Vs - 70 mV (R_L = 20 kΩ) respectively. The positive input amplitude would in the best case be limited to 1.5 mV and 3.0 mV with 1.5 Volt and 3.0 Volts batteries respectively. To be capable of recording signals up to +1 mV, 3 Volt batteries were essential to provide sufficient margin respective to the inputs to deal with various artifacts such as offsets and temperature drifts as described later. The positive peak input voltage is specified with respect to the amplifier's reference. In the present implementation, the amplifier's reference is simply connected to the analog ground. The main advantage is a simple implementation without additional power consumption and a low impedance connection, which maintains the high CMRR. This configuration is optimal if both the positive and negative portions of the bio-signal are relatively the same, otherwise the amplifier's reference could be changed. Generating a virtual ground to be connected to the amplifier's reference could have been easily implemented through a voltage divider using two resistors with high values and the right ratio linking the 3V with the analog ground with the reference connected between the two resistors. By using resistors with high values, the power consumption could have been maintained relatively low but this configuration would increase substantially the impedance at the amplifier's reference and therefore, decrease substantially the CMRR which is critical in differential recording. To generate a virtual ground while providing low impedance at the amplifier's reference, an additional amplifier must be used. This configuration was not chosen because of the additional quiescent current required which imposed some serious restriction on the physical size of the battery that could be used. The standard discharge of the lithium coins with a size

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Abstract

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sufficiently small for our particular implementation is as low as 100 μA. With a 25 μA margin from the maximum quiescent current of the AD627, an additional amplifier would, in the best case, require a standard discharge of 200 μA.

This means that the diameter of the lithium cells would extend for instance from 10.0 mm (CR1025) to a minimum of 20.0 mm (CR2016) in diameter. The discharge current could be increased to the maximum continuous discharge of 0.5 mA for the CR1025 but the voltage at the output of the battery would drop accordingly. Although the voltage at the power rails can drop as low as 1.1V for the AD625, it would reduce the maximum output swing being already under tight restrictions. The same reasoning applies when recording bipolar signals with a single lithium cell. In such a case, a virtual ground must be generated, increasing the drain at the battery's output while reducing the output swing amplitude of the amplifier.

Lithium cells have been selected because of their long shelf life, their light weight, and high energy density relative to older primary cells. There are two main lithium products readily available commercially, namely, the carbon monofluoride coin and the manganese dioxide coin represented with part numbers starting with the standard prefixes BR and CR respectively.

Both types have relatively stable flat discharge voltage. Since conductive carbon is continuously formed during discharge, the internal impedance of the battery does not increase until the end of the discharge. The lithium manganese dioxide (CR-type) is very popular because of its lower cost and wide range of availability compared with the lithium carbon monofluoride (BR-type). Although both types can be used with the present system, the CR-type unlike the BR-type, because of the MnO_2 content, the operating voltage drops slightly over time because of the rise in internal impedance.

The unit has two battery cell holders that typically accept CR1025 lithium batteries. The two 10 mm diameter CR1025 batteries with a weigh of 0.7 gram each have a capacity of 30 mAH per battery, which can provide an operational life of approximately 700 hours minimum and 1000 hours typical of continuous operation between recharges.

D. Filtering

The unit has a 20 dB/dec. bootstrap AC-coupling [2] with a 3-dB cut-off frequency set at 0.5 Hz for baseline drift removal and low-pass filtering above 100 Hz with approximately -20 dB/dec. of attenuation. The high-pass filtering does not require additional components since it is achieved by the limits of the gain versus frequency characteristics of the instrumentation amplifier alone. The amplifier has been selected such that with a gain of 60 dB, a flat response could be observed up to a maximum of 100 Hz with gain attenuation above 100 Hz. Although additional components can be avoided, which is critical in small implementation, the cut-off frequency becomes highly dependent upon the gain value of the unit. For instance,

decreasing the gain to 40 dB would increase the cut-off frequency to approximately 300 Hz in our particular case. Nonetheless, the present implementation provides a perfect match between both the recording bandwidth and a required gain of 60 dB.

The bootstrap AC-coupling requires twice the number of components compared with a typical AC-coupling configuration. But unlike conventional AC-coupling, it maintains a much higher CMRR so critical in differential measurements.

E. Managing Error Artifacts

It is extremely difficult, even with large surface electrodes and very good skin preparation, to provide skin-electrode impedance below 5 K-ohms. In the best case, input impedance of at least 500 K-ohms is required to maintain the loading error below 1%. Assuming that the skin-electrode impedance may vary between 5 K- and 10 K-ohms, 1 M-ohm input impedance would maintain loading errors below the acceptable thresholds between 0.5% and 1%.

Unfortunately, the AD627 has a maximum bias current of 10 nA (2 pA typical) and 15 nA over temperature (10 nA typical) with a typical average temperature coefficient of 20 pA/^{o}C. Because of the AC-coupling, the bias current at each amplifier's input flows through a return path consisting of two resistors of 499 K-ohms each in series in the bootstrap circuit connecting to the analog ground. Over the temperature range, a maximum input offset created by the bias return path can be as high as 15 mV. Although this would be a problem in single-ended recording, in our particular implementation, this large offset would appear at both inputs and ideally be cancelled by the CMRR. Unfortunately, mismatches between the channels prevent a complete cancellation of the bias offset.
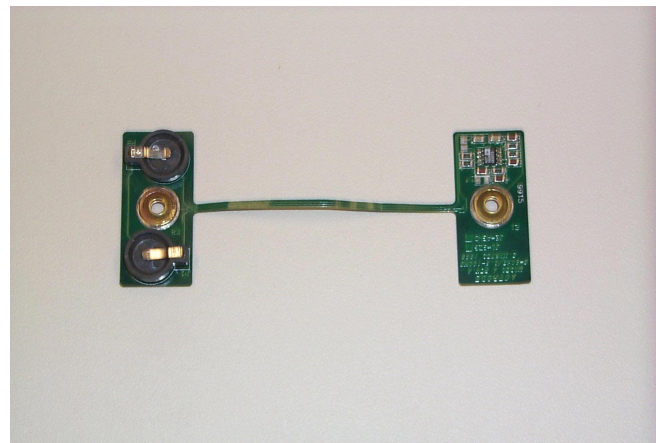

Fig. 1. Photograph of the Actrode unit.

The AD627 has a maximum input offset current of 1 nA (0.3 nA typical) and 5 nA over temperature with a typical average temperature coefficient of 5 pA/^{o}C. This alone creates a worst case input offset at room temperature of 1 mV, which translates onto 1 V at the output. Considering also both the input and output offsets of the amplifier, the

resulting output offset can reach at room temperature a value of approximately 1.2 Volts. With a bio-signal of positive amplitude of 1 mV, we still have approximately 800 mV left at the output (800 μV at the input) prior to saturation. This result translates into approximately 80 kΩ of impedance mismatches at the inputs which should be easily achieved with resistors with a 1% tolerance and a maximum impedance mismatch between electrodes of 5 KΩ.

III. SUMMARY

A new low-power electrode unit with mechanical flexibility has been briefly described. The system, although designed for EMG, can also be adapted to other electrophysiological recording applications such as EOG.

REFERENCES

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[2] "AD624". Data Sheet, Analog Devices, 1992.
[3] "ADG411, 412". Data Sheet, Analog Devices, 1992.
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[5] US Patent 5,300,896